New Type of Double-slit Interference Experiment at Fermi Scale

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A new approach that using polarized photon-gluon collisions reported by STAR Collaboration is used to do tomography of the ultrarelativistic nucleus. The collision can be treated as a double-slit experiment at fermi scale, and solves a mystery last over 20 years in extracting the nuclear radius via vector meson photoproduction.

Gluons, as the propagator of the strong interaction, bind the quarks inside nucleons such as protons and neutrons. With the strong interactions, the quarks and gluons are constrained within the nuclear core instead of existing as free particles. Quantum chromodynamics (QCD) is the most successful theory that describes this strong interaction based upon our current understandings. Beyond this success, QCD does not describe a perfect story on explaining why gluons are not confined within the bounds of protons and neutrons of a nucleus or describing the momentum-dependent parton distribution functions (PDFs) of gluons in a proton. To understand the nature of gluons inside the nuclear matter, mapping the dynamical distribution of gluons inside nuclei is one of the most urgent goals in recent research on experimental nuclear physics.

Now publishing in *Science Advances* [1], the STAR Collaboration has reported a new approach that using polarized photon-gluon collisions to do tomography of the ultrarelativistic nucleus. The work was mainly contributed by a joint team of Brookhaven National Laboratory, Shandong University, and University of Science and Technology of China, led by James Daniel Brandenburg, Zhangbu Xu, Chi Yang, and Wangmei Zha. A mystery last over 20 years in extracting the nuclear radius via vector meson photoproduction has been solved. Even more interesting, a new kind of quantum interference has been observed between two dissimilar particles, showing that this kind of polarized photon-gluon collisions can be treated as a double-slit experiment at fermi scale [2]. The observation also indicates a possible entanglement between dissimilar particles.

To study the gluons, nuclear physicists can shine a light on nuclei. These photons can be emitted via charged particle moving in relativistic velocity such as in e + p, e + A, and A + A collisions. Although there is no electron-ion collider yet, ultra-peripheral A + A collisions (UPCs) where both nuclei pass each other without "breaking" make the research available in ultrarelativistic heavy-ion collisions. The technique is similar to positron emission tomography (PET) used in medical imaging but in fermi scale. The recent measurements in UPCs at RHIC [3, 4] and LHC [5–7] showed that these expected quasi-real photons generated from high-energy nuclear interaction with relativistic speed can be treated as real photon in all possible observables. Furthermore, the measurements from the STAR [4] Collaboration demonstrate that these photons are linearly polarized in the transverse plane, as shown in Fig. 1. In photonuclear interactions, the polarization vector of the spin-1 photon is transferred directly to the produced vector meson (such as ρ^0) and be further transferred into the orbital angular momentum (OAM) of the daughter particles. This will result an alignment between the momentum of daughter particles and the vector meson spin direction, showing as an azimuthal $\cos 2\phi$ modulation in-between them [8].

The key sub-detectors responsible for the success of this tomography of ultrarelativistic nucleus are the Time Projection Chamber (TPC) and Time-Of-Flight (TOF). Both sub-detectors were attributed by joint efforts between the STAR China group and USA groups. TPC upgrade was recently finished [9] and TOF project was completed more than ten years ago [10]. The TPC was used to reconstruct 3D tracks, providing the transverse momenta (p_T) and energy loss (dE/dx) information for particle identification while the TOF was used to reject the contamination from e^+e^-, pp and K^+K^- pairs. With the joint support of both sub-systems, the STAR Collaboration made a precise measurement on the $\rho^0 \to \pi^+ + \pi^-$ photoproduction process, providing the observation on an azimuthal $\cos 2\phi$ modulation effect caused by the ρ^0 spin alignment. It is worthy to mention that the spin alignment is a new and important topic in heavy-ion community since it might shed light on a way to gauge how strong the local fluctuations in the strong force are [11–13]. A very recent STAR's measurement on a vector meson called as ϕ which is composed of a strange quark and its antimatter partner reveals a surprising preference in its spin alignment [14].

In the measurements, since the polarization direction is constrained, the density of gluons can be studied two-dimensionally instead of measured as an average. In previous works, the extracted nuclear radii via vector meson photoproductions were always larger than the expectations which puzzled the field over 20 years. With this 2D imaging technique, the puzzle has been solved by removing the effects from photon transverse momentum

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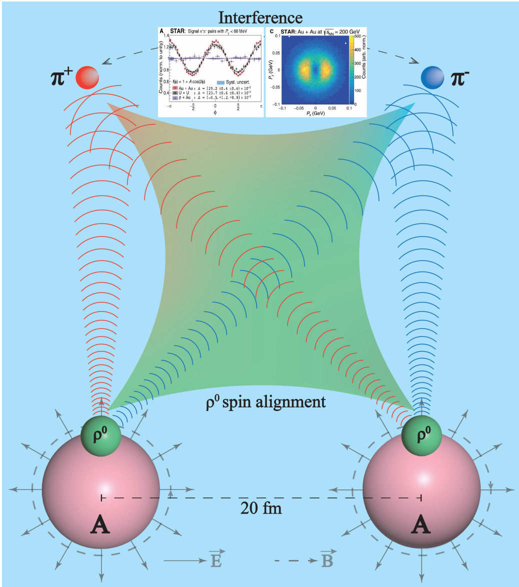

Figure 1: An illustration of the interference pattern in the ρ^0 photoproduction process $\rho^0 \rightarrow \pi^+ + \pi^-$ measured in UPCs at RHIC-STAR. The principle of the interference is similar to double-slit experiment. The two collided ultrarelativistic heavy-ions passed each other with the impact parameter larger than their diameters without "breaking". In the photoproduction process, one nucleus could be either the photon or the Pomeron emitters while the other one acted vice versa. The photoproduced ρ^0 in UPCs will decay to π^+ and π^- pair before its wave functions can interact with the other one. The interference occurs between π^+ and π^- instead of between two ρ^0 or between π^+ and π^- from the same mother particle. The plots of interference effect in the figure are from Ref. [1].

and two-source interference. Furthermore, by comparing the extracted nuclear radii and the previous results of nuclear charge radii [15] , the neutron skin depth of Au and U have been calculated via this new 2D imaging method. The method has the potential to bridge the researches in the current ultrarelativistic heavy-ion collisions which mainly focus on the properties of the extreme hot and dense medium (hot QCD) and the future electron-ion collisions focusing on nuclear structure (cold QCD). The measurements demonstrate that the spin-induced OAM effects open a new way on mapping the nuclear geometry and gluon distribution in heavy-ion quantitatively, extending the physical applications of ultrarelativistic heavy-ion collisions.

One more interesting thing is that the measurements of nonzero ρ^0 spin alignment in Au + Au and U + U collisions demonstrate an entirely new quantum interference behavior between dissimilar particles. Simply by selecting momentum direction along and perpendicular to the photon's motion, as shown in Fig. 1, an interference image can be observed in the momentum phase beside the azimuthal $\cos 2\phi$ modulation. These spin alignment effects were only observed in Au + Au and U + U collisions instead of in p + Au collisions where the photon emitter and the target nuclei (Pomeron emitter) are distinguishable. Considering the lifetime of ρ^0 (about 1fm) and the average impact parameter of the collisions (about 20 fm), this quantum interference may be treated as a good example of entanglement enabled intensity interferometry (E^2I^2) between nonidentical particles [16]. A recent research in quantum optics field is based on the entanglement between lasers with different wavelengths [17] while what was measured at STAR shows the entanglement between π^+ and π^-. In particle physics field, the spin entanglement phenomenon has also been measured between the double-strange baryons Ξ^- and $\overline{\Xi}^+$ via e^+e^- collider, aiming to probe Charge-Parity symmetry and weak phases [18]. The meanings and applications of these discoveries may be beyond our current understandings.

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